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# OPTIMAL INVESTMENT STRATEGIES FOR LIFELINE SYSTEMS UNDER SEISMIC RISKS

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***ABSTRACT***: This paper describes optimal investment strategies for lifeline systems to prevent structural damage due to seismic disaster based on a risk management approach.

Many existing structures are always threatened by various natural hazards including earthquake loads. Actually, those systems constructed prior to 1980 in Japan were designed for a particular seismic load which is smaller than a Level 2 earthquake load. After the 1995 Hyogoken-Nanbu earthquake, revised design guidelines were specified, making old infrastructure design fall below acceptable design limits. It means that these systems are vulnerable to strong earthquakes in the future.

In recent years, Japan's population is shrinking, which has a direct impact into the economy and national budget. In view of this, a more rational decision making process is necessary for future investment of seismic disaster prevention activities of lifeline systems. In which case, maintenance works must be optimized efficiently under the constraint of a limited budget.

In order to obtain an optimal solution among several alternatives, adequate information required to make decisions should be provided in the risk management approach. In this case the incremental cost for each seismic investment strategy can be provided in this study. Numerical examples are also provided to demonstrate its applicability.

***KEYWORDS***: maintenance investment, lifeline, seismic risk

## 1. INTRODUCTION

Risk management approach is necessary to compare alternative maintenance strategies (Koike, 2005) and/or anti-seismic disaster measures for a lifeline system such that investment efficiency (Hoshiya and Yamamoto, 2005) is secured, where the benefit derived from the system, i.e., public welfare in monetary terms, income gains, maintenance costs and various losses due to earthquake risk are taken into consideration.

This study, therefore, provides the method on how to obtain an optimal investment strategy which can answer the questions regarding the acceptable level of strength and how much is affordable cost. Acceptable risk measure and target probability of system failure introduced herein are appropriate indexes for selecting the optimal maintenance strategies.

The seismic reinforcement of trunk lines or transmission networks of major lifeline systems (JWWA, 1997) in Japan has been completed in recent seismic disaster prevention activities. However the distribution and supply networks have many vulnerable structural elements, because any seismic retrofitting are restricted by huge cost when old vulnerable joints are replaced with new seismically high performance joints in buried pipes.

Serviceability at the demand nodes in a transmission network is easily estimated with the connectivity of the network system from the supply nodes to demand nodes. However the serviceability of the distribution and supply system is difficult to estimate, because of its complex configuration of the network and too many demand points from general users.

## 2. DISASTER PREVENTION STRATEGY FOR LIFELINE SYSTEMS

### 2.1 Net present value of lifeline system

In assessing the viability of proposed projects, the project's financial balance or net present value (NPV) at the end of service period is measured.

The project with a positive NPV is accepted, while a project with a negative NPV is rejected. So the NPV at the final stage of the project can be an important measure in assessing the risk of a proposed project.

The net present value $V$ at the service period $T$ is defined as the summation of the social benefit $B$ derived from the system, income gains $I$, daily expenditure $E$, initial cost $C_o$ and maintenance costs $C_M$, which is given in the following formula.

$$V_o = B + I - E - (C_o + C_M) \tag{1}$$

In the private sector, the social benefit term in Eq.(1) does not apply, while public projects do not expect income gains in general. Lifeline projects, on the other hand, have both terms, because a private company has the responsibility in supplying indispensable daily services to all the customers through the lifeline network system. The income gained is used for the daily operation costs, while the social benefit is always generated by the sustainable operating system.

If a lifeline system is always threatened by seismic hazards, a disaster prevention action must be taken in order to keep the system availability with an investment $C_s$ to the seismic reinforcement to the structural elements of the lifeline system. Then the net present value in the risk control phase can be expressed by

$$V = B + I - E - (C_o + C_M + C_S) \tag{2}$$

If we can adopt the risk finance approach with the insurance premium for a business continuation plan (BCP), the net present value will be given in the following form.

$$V = B + I - E - \{C_o + C_M + (C_S - Y) + mY + \alpha\} \tag{3}$$

in which $m, Y$ and $\alpha$ are insurance rate, compensation money and operation fee of an insurance company, respectively.

Since an earthquake hazard is an inevitable phenomenon in Japan, the service loss and restoration cost of the lifeline system must be taken into consideration during its service period. The net present value considering the disaster loss can be expressed by

$$V = B + I - E - (C_o + C_M + C_S) - \Delta B - \Delta I - S \tag{4}$$

where $\Delta\beta, \Delta I$ and $S$ are loss of benefit, loss of income gain and restoration cost after the earthquake, respectively.

It should be noted that the discussion on the discount rate is out of scope in this study in order to emphasize the effect of alternative investment strategies instead of the discount rate to the net present value.

## 2.2 Target probability of system failure

Given the probability of earthquake occurrence, the net present value can be estimated as an expectation:

$$\begin{aligned} E[V] &= V \cdot P[Z<0] + V \cdot P[Z \geq 0] \\ &= V_o - \sum_{j=1}^{3} \left[\Delta B(D_j) + \Delta I(D_j) + S(D_j)\right] \cdot P\left[Z(D_j) < 0 \middle| D_j\right] P\left[D_j \middle| EQ\right] P[EQ] \end{aligned} \tag{5}$$

in which $D_j$ and $P[EQ]$ is the $j$-th structural damage(j=1:minor,j=2:moderate and j=3:major) and the occurrence probability of an earthquake $EQ$.

Now let us fix the $j$-th mode to a single damage mode. So the probability of structural failure $p_f$ is formulated with the performance function $Z$ as

$$p_f = P\left[Z(D_j) < 0 \middle| D_j\right] P\left[D_j \middle| EQ\right] P[EQ] = P[Z<0] \tag{6}$$

Then, the expected value hereunder

$$E[V] = V_o - p_f \cdot \{\Delta B(D_j) + \Delta I(D_j) + S(D_j)\} \tag{7}$$

can be related with the $p_f$.

If seismic investment strategies are discussed based on the $E[V]$, one might misunderstand the seismic effect because of small loss expectation resulting from the small probability of failure. It should be noted that the expectation measure is not adequate for an extreme and rare phenomena as earthquake occurrence. The other approach is to introduce the uncertainty in the net present value as follows.

$$\begin{aligned} P[V>0] &= P[V>0|Z<0]P[Z<0] + P[V>0|Z \geq 0]P[Z \geq 0] \\ &= P[V_o > 0] \\ &- p_f \cdot \left\{P[V_o > 0] - P\left[V_o - \Delta B(D_j) - \Delta I(D_j) - S(D_j) > 0\right]\right\} \end{aligned} \tag{8}$$

Now one may define the ratio of the probability of the net present values as the decision measure of the availability of the project under seismic risk:

$$\gamma = \frac{P[V>0]}{P[V_o > 0]} \tag{9}$$

The target probability of system failure which is appropriate to the positive net present value can be given by

$$p_f^{\text{target}} = (1-\gamma)\cdot \frac{1}{1-\dfrac{P[V_o - \Delta B(D_j) - \Delta I(D_j) - S(D_j) > 0]}{P[V_o > 0]}} \quad (10)$$

**2.3 Investment for seismic disaster prevention**

Lifeline system must be operated for several years, in which Level 1 ground motion will come out at least one or two times, while Level 2 ground motion always threatens the lifeline system during the whole period. For the sake of simplicity, the discussion is focused on the seismic disaster prevention strategy for a single ground motion.

Once the network is physically damaged, the network system service stops. The loss of service corresponds not only to the income loss but also social benefit loss.

2.3.1 Structural damage

Structural damage for a given seismic load is often estimated with the fragility curve. The fragility curve must be furnished for two different limit states, serviceability limit state and ultimate limit state.

The major damage mode can be defined as the state that the seismic load exceeds the critical strength of the ultimate limit state. The fragility curve for the major damage mode is given by

$$p_f(D_{major}|s) = P[R^{major} - S < 0 | S = s] \quad (11)$$

The minor damage mode, on the other hand, is defined as the state that the seismic load is less than the critical strength of the serviceability limit state.

So the fragility curve for minor damage mode is expressed by

$$p_f(D_{\text{minor}}|s) = P[R^{\text{minor}} - S > 0 | S = s] \quad (12)$$

The moderate damage mode is the set which does not belong to both of the major and minor damage modes.

Restoration cost for the damaged network after an earthquake can be estimated in the following way.

$$C(t|D) = \int_A \lambda[D(x)]\cdot L(x;t)dx \quad (13)$$

in which *A*,*D(x)*,*L(x;t)* and *λ[D(x)]* are the supply district area, damage mode at the location x, stretch of the pipeline and restoration cost per unit length.

2.3.2 Seismic disaster prevention

If a prior reinforcement is done for a network as a seismic disaster prevention measure, the physical damage is decreased, so that the corresponding serviceability damage is also improved.

In this situation, the fragility curve of major damage mode after the reinforcement is given by

$$\hat{p}_f(D_{major}|s) = P[\hat{R}^{major} - S < 0 | S = s] \quad (14)$$

The fragility curve for the minor damage mode is

$$\hat{p}_f(D_{\text{minor}}|s) = P[\hat{R}^{\text{minor}} - S > 0 | S = s] \quad (15)$$

Fig.1 shows the schematic example how the fragility curve is improved by the prior reinforcement.

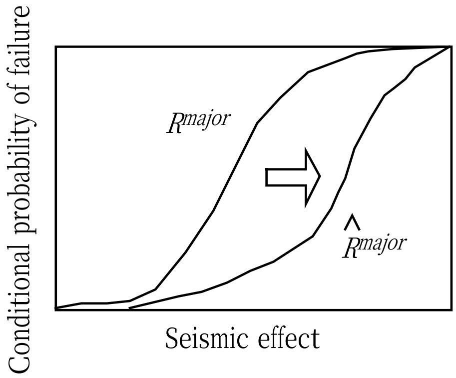


Figure 1 Fragility curve shifted by reinforcement

2.3.3 Social benefit

When the lifeline resumes the operation, the social benefit starts. For the sake of simplicity, the amount of social benefit is assumed to be proportional to the gross domestic production (GDP). Fig.2 shows the trend of social benefit during the life cycle period.

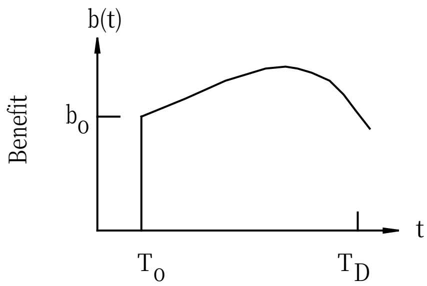


Figure 2 Trend of social benefit during the life cycle period

The loss of benefit is shown in Fig.3 as the shaded area when an earthquake occurs at the time *T* and restoration process resulting from structural damages of the system resumes up to *Δt*.

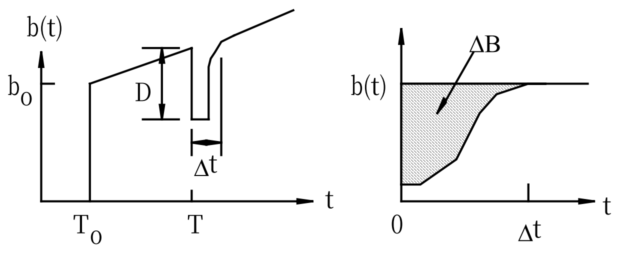


Figure 3 Loss of benefit under seismic damages

$$b_k(t) \approx b_o \cdot \frac{GDP(t)}{GDP(T_o)} \cdot \frac{A_k}{\sum_{k=1}^{NK} A_k} \qquad (16)$$

in which $b_o$ is a social benefit per year and is given by the ratio of $B_o/(T_D-T_o)$, while $GDP(t)$ and $A_k$ are the gross domestic production of the $t$-th year and area of the $k$-th distribution service district in the networks system, respectively.

$$B = \int_{T_o}^{T_D} \sum_{k=1}^{NK} b_k(t)dt \quad , \quad \Delta B \approx \Delta t \cdot \sum_{k=1}^{NK} b_k(t) \qquad (17)$$

2.3.4 Optimal investment strategies

In order to select the most appropriate investment for the seismic disaster prevention work, there are several approaches;

1)to reinforce the most vulnerable structural elements,

2)to provide the most effective investment which increases the positive NPV, or

3)to furnish the real time control system for the risk and crisis management immediately after the quake.

## 3. STRUCTURAL DAMAGE OF LIFELINE SYSTEMS

### 3.1 Definition of damage modes

The structural damage states for lifeline network are defined as

(a) Major damage

At least one link segment is in a major damage state along the lifelines.

(b) Moderate damage

All the segments are not in the minor or major damage state along the lifelines.

(c) Minor damage

All the link segments are in the minor damage state along the lifelines.

In the same way, the structural damage states for the station system are defined as

(d) Major damage

At least one station is in a major damage state in the network system.

(e) Moderate damage

All the stations are not in the minor or major damage state in the network system.

(f) Minor damage

All the stations are in the minor damage state in the network system.

The lifeline network system includes supply stations, transmission lines, substations and service networks to demands. These structures can be classified into two typical elements which are characterized as links and nodes. Link elements are transmission lines and distribution networks, while node elements are system control facilities and reservoir structures.

3.1.1 Link Element

Limit state for major damage mode of a link element:

$$Z_i^{major} = \delta_{cr}^{major} - \delta_i \qquad (18)$$

Limit state for minor damage mode of a link element:

$$Z_i^{\min or} = \delta_{cr}^{\min or} - \delta_i \qquad (19)$$

Link element can be modeled as a poly-line passing through many meshes which belong to various soil conditions. One segment which is located in a mesh is defined as an element. In Fig.4, elements 1, 2 and 3 are located at their own meshes. Element 1 and 2 are connected at the mesh boundary.

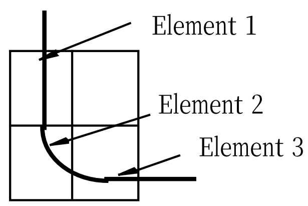


Figure 4 An element model of a passing through many meshes.

3.1.2 Node element

Limit state for major damage mode of a node structure:

$$ZN_j^{major} = \alpha_{cr}^{major} - \alpha_j \tag{20}$$

Limit state for minor damage mode of a node structure:

$$ZN_j^{\min or} = \alpha_{cr}^{\min or} - \alpha_j \tag{21}$$

The station has its own probability of failure which depends on the damage occurrences of facilities in the station system. In order to classify the undamaged node in the sense of mathematical network system from the actual damaged node, the undamaged node and fictitious sub-node are introduced and the probability of node damage can be estimated with that of the facility damage in the station.

Fig.5 is an extended node model with undamaged node and fictitious sub-nodes.

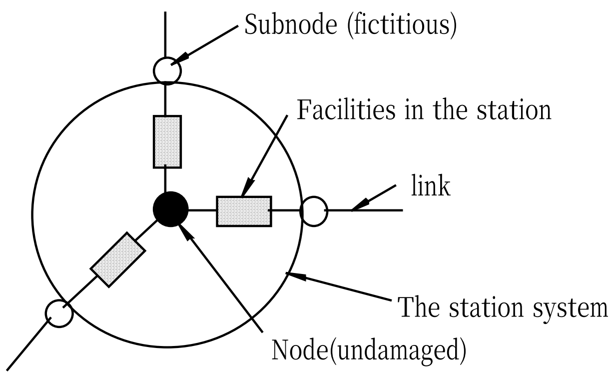


Figure 5 A node model with a fictitious sub-nodes

## 3.2 Definition of the system damages of the network system

3.2.1 Definition of Link and Node Damages in the transmission Network Systems

1)Definition of Link Damage

It should be noted that a link is a series system of several line elements (i.e $NL_k$) connecting neighboring nodes.

Major damage of the $k$-th link:

$$E_k^{major} = \bigcup_{i=1}^{NL_k} E\left[Z_i^{major} < 0\right] \tag{22}$$

Moderate damage of the $k$-th link:

$$E_k^{\text{moderate}} = \overline{E}_k^{major} \bigcap \overline{E}_k^{\text{minor}} \tag{23}$$

Minor damage of the $k$-th link:

$$E_k^{\text{minor}} = \bigcap_{i=1}^{NL_k} E\left[Z_i^{\text{minor}} > 0\right] \tag{24}$$

2)Definition of Node Damage

Major damage of the $j$-th node:

$$E_j^{major} = E\left[ZN_j^{major} < 0\right] \tag{25}$$

Moderate damage of the $j$-th node:

$$E_j^{\text{moderate}} = \overline{E}_j^{major} \bigcap \overline{E}_j^{\text{minor}} \tag{26}$$

Minor damage of the $j$-th node:

$$E_j^{\text{minor}} = E\left[ZN_j^{\text{minor}} > 0\right] \tag{27}$$

3)Definition of extended link damage

An extended link have a series system of a link, station and a sub-node as shown in Fig.6.

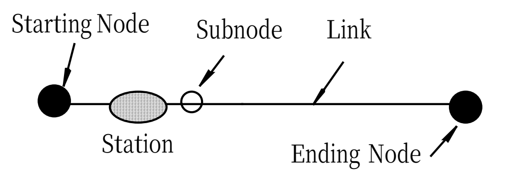


Figure 6 An extended link model

Major damage of an extended link:

$$E_k^{major} = \left\{\bigcup_{i=1}^{NL_k} E\left[Z_i^{major} < 0\right]\right\} \bigcup \left\{E\left[ZN_j^{major} < 0\right]\right\} \tag{28}$$

Moderate damage of an extended link:

$$E_j^{\text{moderate}} = \overline{E}_k^{major} \bigcap \overline{E}_k^{\text{minor}} \tag{29}$$

Minor damage of an extended link:

$$E_k^{\text{minor}} = \left\{\bigcap_{i=1}^{NL_k} E\left[Z_i^{\text{minor}} > 0\right]\right\} \bigcap \left\{E\left[ZN_j^{\text{minor}} > 0\right]\right\} \tag{30}$$

3.2.2 Definition of structural damage in the distribution network system

A distribution network system has huge networks in each mesh. So we focused our attention on the structural damages of all the networks instead of the system connectivity damage estimations

Structural damages of networks are summarized with the total number of damage points along all the links in each mesh.

Major damage points of the $k$-th mesh:

$$n_k^{major} = \sum_{l=1}^{NL_k} v_{kl}^{major} L_{kl} \tag{31}$$

Moderate damage points of the $k$-th mesh:

$$n_k^{\text{moderate}} = \sum_{l=1}^{NL_k} \nu_{kl}^{\text{moderate}} L_{kl} \tag{32}$$

Minor damage points of the *k*-th mesh:

$$n_k^{\text{minor}} = \sum_{l=1}^{NL_k} \nu_{kl}^{\text{minor}} L_{kl} \tag{33}$$

In which $NL_k, \nu_{kl}, L_{kl}$ are total numbers of various links in the *k*-th mesh, damage occurrence rate per km for each damage mode and the total length of the *l*-th link in the *k*-th mesh.

**3.3 Analytical formulation of the connectivity damages of the transmission network system**

3.3.1 Definition of connectivity model from the *M*-th node to *N*-th node

The *t*-th connectivity is given as a series system of several links, the total number of which is equal to $NC_t$ .

$$C_t^{MN}(damage) = \sum_{s=S_1}^{NC_t} E_s^{damage} \tag{34}$$

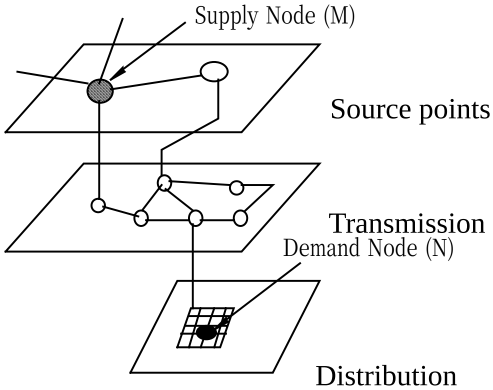


Figure 7 Connectivity model

3.3.2 Definition of the *t*-th connectivity damage among several connectivity systems from supply nodes to demand nodes

Major damage of a connectivity:

$$C_t^{MN}(major) = \bigcup_{s=S_t}^{NC_t} E_s^{major} \tag{35}$$

Moderate damage of a connectivity:

$$C_t^{MN}(\text{moderate}) = \overline{C}_t^{MN}(major) \bigcap \overline{C}_t^{MN}(\text{minor}) \tag{36}$$

Minor damage of a connectivity:

$$C_t^{MN}(\text{minor}) = \bigcap_{s=S_t}^{NC_t} E_s^{\text{minor}} \tag{37}$$

3.3.3 Definition of probability of connectivity damage from supply node *M* to demand node *N*

The connectivity from supply node *M* to demand node *N* is assumed to be equal to *NC* set of the series system which is composed of several links.

Probability of major damage of a connectivity:

$$P\left[C^{MN}(major)\right] = \bigcap_{t=1}^{NC} P\left[C_t^{MN}(major)\right] \tag{38}$$

Probability of moderate damage of a connectivity:

$$P\left[C^{MN}(\text{moderate})\right] = 1 - P\left[C^{MN}(major)\right] - P\left[C^{MN}(\text{minor})\right] \tag{39}$$

Probability of minor damage of a connectivity:

$$P\left[C^{MN}(\text{minor})\right] = \bigcup_{t=1}^{NC} P\left[C_t^{MN}(\text{minor})\right] \tag{40}$$

3.3.4 Calculation of connectivity from supply node to demand node of the damaged network

Monte Carlo Simulation is used to obtain the probability of the connectivity in the damage network. As analytical tool, a transfer matrix from the supply nodes to the demand nodes is introduced, the element of which is composed from the probability $p_{MN}$ of the supply node *M* to the demand node *N* in the damaged network.

The damage state vector $A_j$ of the nodes after the *j*-th step is given by

$$A_j = H_j(\underline{D}_k) A_{j-1} \quad , \qquad j = 1, 2 \cdots, NA \tag{41}$$

where $A_o, \underline{D}_k$ and $H_j$ are the initial damage state vector of the nodes, the *k*-th damage modes for all the links and the transfer matrix at the *j*-th step. *NA* is a number of steps in transferring from the source nodes to the farthest nodes.

## 4. NUMERICAL STUDIES

### 4.1 Network model

Structural damage of buried pipelines due to seismic effect can be evaluated with relative displacements and surface strains in the ground response or permanent deformation at the fault crossing or uneven settlement in the liquefiable areas. The relative displacement $\delta$ is calculated in the following equation.

$$\delta = \frac{2}{\pi^2} S_V\left(T_G\right) \cdot T_G \cdot \left\{1 - \cos\left(\frac{2\pi}{L} \cdot \Delta l\right)\right\} \qquad (42)$$

in which $S_V(T_G)$, $T_G$, $L$ and $\Delta l$ are velocity response spectrum, typical period and its corresponding wave length of the surface ground, and unit pipe length in meter, respectively.

Fig.8 is a schematic example of the transmission pipelines, while the distribution network is connected at several nodes in the transmission pipeline. Since the GIS data of the distribution network is not available, a simplified rectangular mesh model is introduced instead of the real distribution networks in order to evaluate both the structural and connectivity damages.

Table 1 shows that each distribution network has three kinds of pipelines such as cast iron pipe (CIP), ductile cast iron pipe (DIP) and steel pipe (STEEL). The pipe diameters ranges from 75 mm to 500 mm.

The numbers of supply nodes are varied from 2 to 7 among these seven districts shown in Table 1.

Table 1 Pipeline dimensions of seven distribution districts (A,B,C,D,E,F,G) in the water network

The major damage occurrence rate per km along the pipeline for a given seismic load $s$ is expressed by

$$\nu^{major}(s) = \frac{1000}{\Delta l} \cdot p_f\left(D_{major} \middle| s\right) \qquad (43)$$

The nodes of the network system are classified into a source in a square and reservoir tank or pumping station in a circle in Fig.8.

A scenario earthquake (Tachikawa fault earthquake) of magnitude 6.6 is used as the input force.

The structural damages of links and nodes in the network system can be evaluated with the fragility curves for ground responses.

Figure 8 A schematic example of the transmission pipelines

| Diameter | Length (m) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A district | | | B district | | | C district | | | D district | | |
| | CIP | DIP | STEEL | CIP | DIP | STEEL | CIP | DIP | STEEL | CIP | DIP | STEEL |
| 75 | 16765 | 2558 | 2001 | 3221 | 2640 | 2161 | 3943 | 1589 | 0 | 4787 | 6842 | 0 |
| 100 | 40713 | 72434 | 9166 | 17934 | 59426 | 6255 | 24186 | 102704 | 4312 | 2662 | 81731 | 1426 |
| 150 | 15706 | 44739 | 2090 | 5817 | 18225 | 2165 | 5128 | 32530 | 4142 | 8479 | 23905 | 3934 |
| 200 | 14391 | 42334 | 3833 | 4604 | 17464 | 453 | 4839 | 53804 | 294 | 4738 | 20091 | 1390 |
| 250 | 295 | 156 | 37 | 1624 | 181 | 72 | 1192 | 54 | 709 | 52 | 53 | 0 |
| 300 | 9564 | 18011 | 6021 | 7023 | 6332 | 331 | 5836 | 8637 | 749 | 3620 | 14898 | 925 |
| 350 | 5254 | 3676 | 845 | 4578 | 3408 | 0 | 5330 | 7459 | 206 | 2820 | 14049 | 2121 |
| 400 | 5941 | 3699 | 245 | 3925 | 2845 | 0 | 1539 | 6285 | 0 | 0 | 0 | 879 |
| 450 | 1094 | 7 | 0 | 1010 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 500 | 2364 | 3680 | 48077 | 12 | 101 | 21572 | 0 | 4509 | 24386 | 0 | 5260 | 23023 |
| subtotal(m) | 112087 | 191294 | 72315 | 49748 | 110622 | 33009 | 51993 | 217571 | 34798 | 27158 | 166829 | 33698 |
| area(km$^2$) | 40.25 | | | 10.09 | | | 14.81 | | | 17.1 | | |
| supply nodes | 6 | | | 2 | | | 3 | | | 6 | | |
| streets in x-axis | 5 | | | 5 | | | 6 | | | 4 | | |
| streets in y-axis | 5 | | | 5 | | | 7 | | | 5 | | |

| Diameter | Length (m) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | E district | | | F district | | | G district | | |
| | CIP | DIP | STEEL | CIP | DIP | STEEL | CIP | DIP | STEEL |
| 75 | 4184 | 1086 | 0 | 5828 | 556 | 1287 | 3201 | 2199 | 4279 |
| 100 | 22331 | 94126 | 2162 | 20216 | 139104 | 1498 | 10306 | 155136 | 2585 |
| 150 | 11143 | 29079 | 1546 | 11640 | 47331 | 1658 | 5017 | 50006 | 1620 |
| 200 | 6644 | 29789 | 761 | 7067 | 32125 | 683 | 6870 | 42076 | 1084 |
| 250 | 0 | 0 | 167 | 2514 | 273 | 0 | 1203 | 244 | 489 |
| 300 | 3004 | 24901 | 1166 | 3116 | 22456 | 1398 | 4064 | 20104 | 698 |
| 350 | 0 | 6155 | 743 | 920 | 4903 | 1753 | 5401 | 17955 | 254 |
| 400 | 0 | 506 | 95 | 0 | 5861 | 93 | 0 | 5230 | 156 |
| 450 | 0 | 2479 | 51 | 0 | 0 | 0 | 0 | 0 | 2009 |
| 500 | 0 | 9995 | 35482 | 262 | 9328 | 19907 | 2663 | 8847 | 123133 |
| subtotal(m) | 47306 | 198116 | 42173 | 51563 | 261937 | 28277 | 38725 | 301797 | 136307 |
| area(km$^2$) | 18.6 | | | 20.39 | | | 23.11 | | |
| supply nodes | 3 | | | 5 | | | 7 | | |
| streets in x-axis | 5 | | | 6 | | | 8 | | |
| streets in y-axis | 6 | | | 7 | | | 9 | | |

The connectivity failure of the transmission network controls the serviceability of the distribution and supply network system.

### 4.2 Serviceability analysis

The network system has intrinsic characteristics that the physical damage does not always correspond to the connectivity damage because of the redundancy of the network. These characteristics are assessed for the simplified rectangular meshes of the distribution networks in Table 1. Figure 9 shows a numerical result of its relationship.

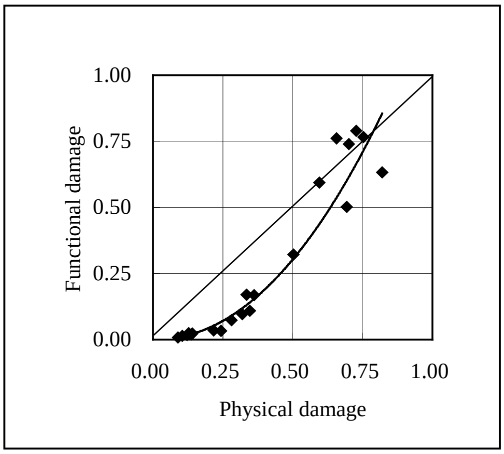


Figure 9 Relationship between physical and connectivity damages.

Figure 9 reveals the redundancy effect that the physical damage is larger than the connectivity damage. Figure 10 shows that the NPV divided by $C_o$ is calculated by Eq.(4) for various damage occurrence rates $\nu$. This result suggests that the NPV decreases for larger $\nu$, while the NPV of districts (B) and (D) show comparatively better performance than those of the other districts. District (A) which has the lowest value, on the other hand, is effectively improved by the reinforcement for the seismic disaster prevention.

Restoration cost for structural damages at the $k$-th district are modeled as $S_k(D_{minor})=0$ , $S_k(D_{moderate})=e\xi_\kappa C_o$, $S_k(D_{major})= \xi_\kappa C_o$.
in which $\xi_\kappa$ is a ratio of the pipe length of the $k$-th district per total elongation of Kawasaki water distribution system, and $e$ is a parameter of $0<e<1$ for moderate damage mode. The net present value $V_o$ is assumed to be equal to $\zeta C_o$ with a constant $\zeta$.

## 5. CONCLUSIONS

The optimal disaster prevention strategy is discussed for a lifeline system such that investment efficiency is secured, where the benefit derived from the system, income gains, maintenance costs and various losses due to earthquake risk are taken into consideration.

A case study is implemented to compare alternative strategies for the water supply system in Kawasaki City. It is found that the water supplying district of the lowest value is effectively improved by the reinforcement for the seismic disaster prevention.

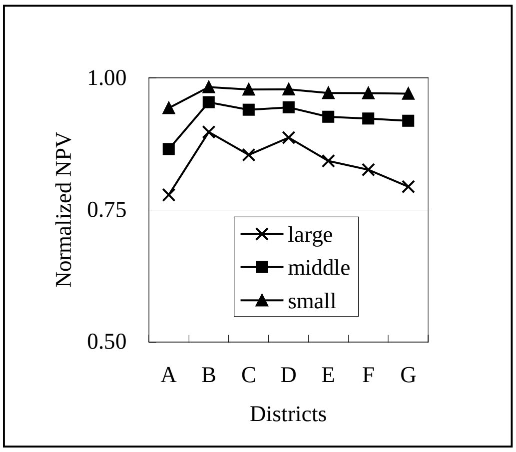


Figure 10 Normalized NPV of the distribution networks in seven districts for various damage occurrence rates.


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